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# A new method to optimize protection of the organs at risk allows to regain coverage and homogeneity in the Planning Target Volume

## Novo método para a otimização da proteção dos Organs at Risk permite a recuperação da cobertura e homogeneidade em Planning Target Volume

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**Abstract**
The construction of auxiliary structures within the Planning Target Volume (PTV) is proposed as a method to recover coverage and homogeneity, and to optimize the protection of the organs at risk (OARs) in radiotherapy treatment plans. To this purpose, it was performed the Volumetric Modulated Arc Therapy (VMAT) treatment planning of the “mock prostate” test. Three plans were optimized in the Eclipse™ treatment planning system. In plan 1 (P1), it was defined as an initial objective function only for the PTV. Then, the dose received by the OARs was restricted, guaranteeing the PTV level of coverage. Plan 2 (P2) used the same dose-volume objectives for the PTV as in P1, but more restrictive dose constraints were set for the OARs. From the dose distribution obtained in P2, it was built auxiliary sub volumes contained within the PTV to regain coverage and homogeneity in plan 3 (P3). To this end, it was compared the coverage ($D_{95\%}$), the Homogeneity Index (HI) and dose-volume histogram for the PTV, and OARs dose sparing for rectum and Bladder. P1 and P3 resulted in similar PTV coverage and HI values, however, the OARs received a lower dose in P3. Despite in P2 it was achieved a higher OARs protection, the PTV coverage and HI were considerably reduced. In this sense P3 allowed us to reach the best balance between coverage, HI, and OARs protection. Because of these results, it has been shown that the introduction of auxiliary structures as target sub volumes constitute a powerful and easy to implement tool in the treatment planning optimization process and can be employed in any pathology that requires VMAT.
**Keywords**: VMAT; ICRU 83; homogeneity index; dose coverage; OARs protection.

***Resumo***
A construção de estruturas auxiliares dentro do *Planning Target Volume (PTV)* é proposta como método para recuperar a cobertura e a homogeneidade e para otimizar a proteção dos *Organs at Risk (OARs)* em planos de tratamento de radioterapia. Com esse fim, foi desenvolvido o plano de tratamento *Volumetric Modulated Arc Therapy (VMAT)* para o teste de "*mock prostate*". Foram otimizados três planos no sistema de planejamento de tratamentos *Eclipse™*. No plano 1 (P1), foi definida uma função objetivo unicamente para o PTV. Logo disso, foi restrita a dose recebida pelos OARs, garantindo o nível de cobertura do PTV. No plano 2 (P2), foram usados os mesmos objetivos dose-volume, mas se acrescentaram para os OARs. A partir da distribuição de dose obtida em P2, no plano 3 (P3), foram construídos sub volumes auxiliares contidos dentro do PTV para recuperar cobertura e homogeneidade. Para este fim foram comparados a cobertura ($D_{95\%}$), o índice de homogeneidade (HI), e o histograma dose-volume para o PTV, e a proteção dos OARs para o reto e a bexiga. P1 e P3 resultaram em valores de cobertura e HI para o PTV, no entanto, os OARs receberam uma dose menor em P3. Apesar que através de P2 tivesse uma proteção mais alta para os OARs, a cobertura e o HI do PTV foram reduzidos consideravelmente. Nesse sentido, P3 permitiu alcançar o melhor balanço entre cobertura, HI, e proteção dos OARs. Portanto, esse trabalho mostrou que o uso de estruturas auxiliares como sub volumes alvo costitui uma ferramenta potente e de fácil implementação no processo de otimização de planos de tratamento.
**Palavras-chave***:* VMAT; ICRU 83; índice de homogeneidade, cobertura de dose, proteção dos OARs.

## 1. Introduction

Since its introduction in 2007 (1), the use of the Volumetric Modulated Arc Therapy (VMAT) technique has been widely adopted by the radiotherapy community given the high degree of control of dose levels it brings over the treatment regions, mainly in structures with complex shapes. VMAT enables high dose conformation at the target volume, improved sparing of organs at risk (OAR), and reduction of the treatment delivery time (2, 3).

In the planning of treatments with VMAT, there are three parameters that can be varied: i) the radiation beam profile (modulated through the Multi-Leaf Collimator motion), ii) the speed of rotation of the gantry, and iii) the dose rate (1,2,3,4). The physically possible combinations of these parameters are determined by inverse planning algorithms. In these algorithms, it is defined an objective function, with dose-volume constraints and priority values over the structures of interest (target and OARs), to inversely find the optimal treatment plan (1, 5, 4).

The optimization process usually seeks to first define the objective function to achieve homogeneity of the absorbed dose in the planning target volume (PTV), and then, modify the dose-volume objectives to reduce the absorbed dose in the OARs while maintaining coverage in the target (5). Restricting the dose in the OARs while maintaining coverage in the PTV has several implications. It will not achieve the desired dose reduction in the OARs and therefore, it is a clinically unacceptable treatment plan. Additionally, if the dose in the OARs is too limited, the coverage and homogeneity of the dose distribution within the PTV also decrease.

In recent years, several automatic optimization algorithms have been developed to improve the efficiency and quality of treatment planning (6). However, in many radiotherapy facilities around the world, the optimization of the treatment plan is still done manually. In this case, the planning methods depend on the experience of the Medical Physicist planner as well as several trial-and-error attempts to evaluate the impacts on the quality of the plan (7,8).

In this work it is presented a manual VMAT treatment planning optimization strategy that allows to efficiently reduce the dose in the OARs while maintaining the homogeneity and coverage of the dose in the PTV within acceptable values.

## 2. Materials and Methods

The treatment planning of the “mock prostate” test, suggested by Task Group 119 of the American Association of Physicist in Medicine (see Figure 1), was performed with the VMAT technique by using a 6 MV photon beam, emitted by a Varian Trilogy linear accelerator (9).

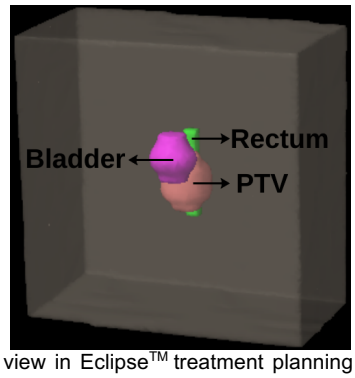


**Figure 1.** 3D view in Eclipse™ treatment planning system of the volumes for the "mock prostate" test of the TG-119.

Plans were created with the Eclipse™ Treatment Planning Systems (TPS), versions 13.6 (Varian Medical Systems, Palo Alto, CA) by employing two complete arcs with isocenter at the PTV, and the collimator rotated by 30° and 330° respectively. The inverse optimization process of the treatment plan was performed with the Photon Optimizer algorithm (PO), version 16.623, and the AAA algorithm, version 11031 (Varian Medical Systems, Palo Alto, CA) with calculation grid size of 0.25 cm for the dose calculations. Three versions of the treatment plan were carried out for a hypofractionated scheme of 3 Gy per fraction up to a total dose of 60 Gy following the sequence shown in the diagram of Figure 2. In the first two, the input parameters of the objective function were varied for the OARs while maintaining the same parameters for the PTV. On the other hand, in the third one, auxiliary structures within the PTV were implemented.

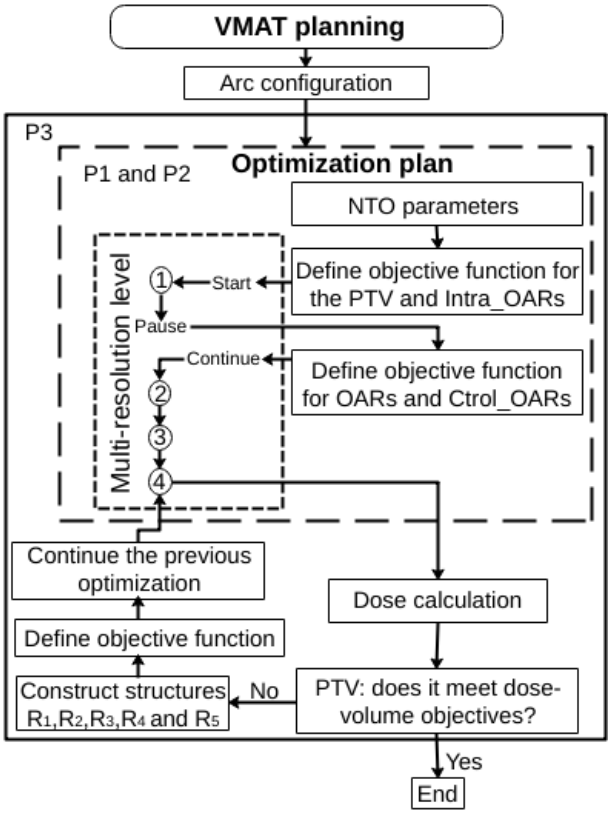


**Figure 2.** Flow diagram of the optimization process for P1, P2 (dotted line box) and P3 (solid line box) with the Photon Optimizer algorithm. The objective function for P3 is the same as in P2 for the PTV and OARs, and the dose calculated in P2 is used as an intermediate dose to continue the previous optimization in the multi-resolution level 4.

For the overlap between the OARs and the PTV, it was used the Crop Structure tool to create two structures, corresponding to Ctrol_OAR and Intra_OAR, with the aim of avoiding conflict between the protection of the OARs and the coverage of the PTV in the optimization algorithm, as presented in Figure 3a and 3b respectively. Ctrol_OAR is obtained by removing the OAR volume that extends inside the PTV with a margin of 0.3 cm and Intra_OAR is the result of extracting the OAR region that is inside the Ctrol_OAR structure.

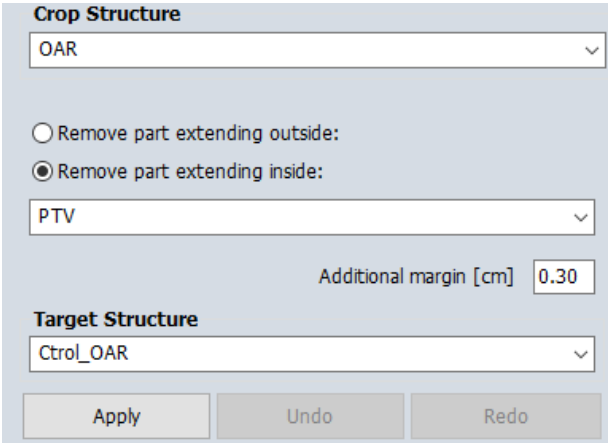


**Figure 3.** View of the Crop Structure tool available in Eclipse™ TPS, with the operations to obtain the volumes a) Ctrol_OAR and b) Intra_OAR.

### *2.1. Treatment plans for the "Mock Prostate" test*

Now it will be present the details of the three plans, as illustrated in Figure 2.

- *Treatment plan 1 (P1).* At the beginning of the optimization process (multi-resolution level 1) the objective function was defined only for the PTV; a maximum (upper) and a minimum (lower) dose–volume objective was set to reach the prescription dose. Complementary to this, once the PTV reaches the desired coverage, the process is paused to incorporate the OAR objective function. Then, it was introduced three upper objectives to restrict the dose received by the OARs (Ctrol_rectum and Ctrol_bladder, see Table 1). Along with this plan it was maintained PTV coverage. Subsequently, the optimization process is resumed.
- *Treatment Plan 2 (P2)*. The optimization process starts with the same dose-volume objectives for the PTV as in P1, but once it is paused, more restrictive upper objectives are implemented for the OARs (see Table 1).
- *Treatment Plan 3 (P3)*. Finally, a set of auxiliary structures are incorporated as target sub volumes of the PTV, seeking to regain homogeneity, coverage and local control over low and high dose regions (see section 2.1.1).

It must highlight that the introduction of very restrictive objectives for the OARs protection commonly leads to regions of the PTV that do not attain the full prescription dose as well as to regions exceeding this value at the optimization process (as it could be the case of P2.

**Table 1.** Optimization parameters of the objective function for the PTV and OARs employed in this work.

| Plan | Structure | Objective | Volume (%) | Dose (Gy) | Priority |
|---|---|---|---|---|---|
| P1 | PTV | Upper | 0.0 | 60.0 | 0.0 |
| | | Upper | 0.0 | 62.4 | 100.0 |
| | | Lower | 100.0 | 62.2 | 100.0 |
| | Intra Rectum | Upper | 0.0 | 62.4 | 100.0 |
| | Ctrol Rectum | Upper | 16.0 | 34.9 | 60.0 |
| | | | 7.4 | 39.4 | 60.0 |
| | | | 1.0 | 43.0 | 60.0 |
| | Intra Bladder | Upper | 0.0 | 62.4 | 100.0 |
| | Ctrol Bladder | Upper | 14.0 | 29.9 | 60.0 |
| | | | 7.0 | 31.5 | 60.0 |
| | | | 2.0 | 35.1 | 60.0 |
| P2 | Intra Rectum | Upper | 0.0 | 62.4 | 100.0 |
| | Ctrol Rectum | Upper | 39.0 | 4.8 | 60.0 |
| | | | 19.2 | 7.5 | 60.0 |
| | | | 3.0 | 12.0 | 60.0 |
| | Intra Bladder | Upper | 0.0 | 62.4 | 100.0 |
| | Ctrol Rectum | Upper | 39.7 | 0.9 | 60.0 |
| | | | 19.0 | 2.0 | 60.0 |
| | | | 2.7 | 5.0 | 60.0 |
| P3 | PTV, $R_1$, $R_2$, $R_3$, $R_4$, $R_5$ | Upper | 0.0 | 60.0 | 0.0 |
| | | Upper | 0.0 | 62.4 | 100.0 |
| | | Lower | 100.0 | 62.2 | 100.0 |
| | OARs | Upper | Same as in P2 | | |

Source: The Author

#### *2.1.1 Construction of auxiliary structures to regain coverage and homogeneity in the PTV*

For P3, a set of 5 auxiliary structures are created from the isodose curves obtained in P2: three for regions of the PTV receiving doses below the prescription (cold spots) and two more for areas exceeding this value (hot spots). The purpose of the first three regions is to recover coverage and to ensure that 98% of the PTV receives a dose equal or close to the prescription, which can be obtained from the following relationship for every region (denoted by Ri),

$$R_i(V_i) = PTV - V_i, \quad (1)$$

for i = 1, 2 ,3. $V_1$ is obtained from the isodose level covering 98 % of the PTV ($D_{98\%}$), and $V_2$ and $V_3$ are the receive 98% and 100% of the, respectively (see Figure 4c). In this regard, $R_3$ contains $R_2$ and $R_1$, and $R_2$ contains $R_1$ (see Figure 4a).

To control regions having doses values higher than the prescription, two more sub volumes are created within the PTV. The first one and the second one is the regions that receive more than d% (d%>100%) and more than d'% (d'%>d%) of the prescription dose ($R_4$ and $R_5$, respectively, as shown in Figure 4b).

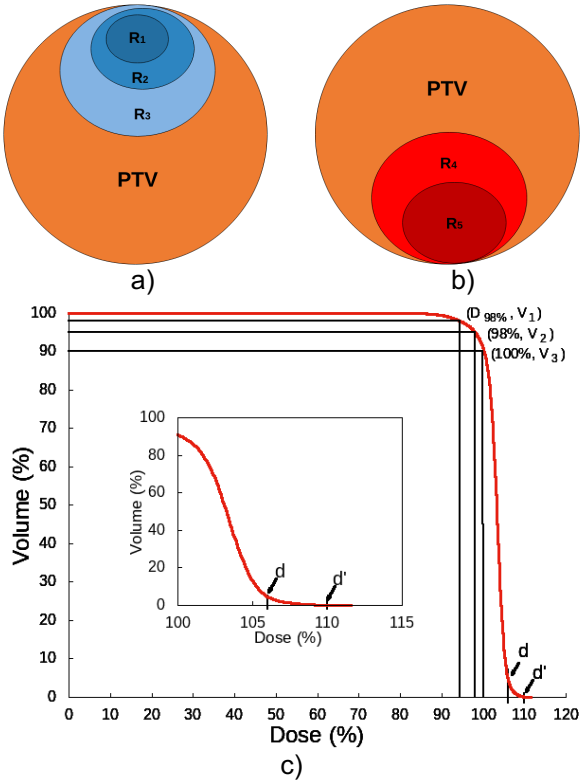


**Figure 4.** Scheme of the auxiliary structures created to a) recover coverage and b) reduce the high dose regions within the PTV. c) Example of DVH showing the isodose values to construct structures $V_1$, $V_2$, $V_3$, $R_4$ and $R_5$. Inset: tail region of the DVH showing the d and d' positions. Here $D_{98\%}$ = 94.3%, d = 106%, and d' = 110%, relative to the prescription dose.

The values of d and d' have to be chosen according to the tail region of the DVH (see Figure 4c). For $R_4$, d must be selected as the value where the curve decay changes (high dose values that correspond to 5% or less of the volume at the DVH, as shown in inset of figure 4c). On the other hand, for $R_5$, d' is defined as the value close to the dose maximum. In this regard, $R_5$ is a region inside R4 (see Figure 4b). Once the auxiliary structures are defined, the optimization process must be resumed from the fourth stage of the multi-resolution level (using P2 as an intermediate dose for optimization), introducing the same dose-volume objectives for the target sub volumes of the PTV in P2 (from $R_1$ to $R_5$, as shown in Figure 2 and Table 1). Finally, the volumes $V_1$, $V_2$, $V_3$, $R_4$ and $R_5$ are generated by employing the "Convert Isodose Level to Structure" tool, available in Eclipse™ TPS.

*2.2. Evaluation of treatments plans*

From the dose-volume histograms (DVH) obtained by the three versions of the treatment plan, it is possible to evaluate their quality by means of the dose that covers 95% of the PTV ($D_{95\%}$), the mean dose ($D_{mean}$), maximum dose ($D_{max}$) and homogeneity index (HI), defined as (5),

$$HI = \frac{D_{2\%} - D_{98\%}}{D_{50\%}}, \quad (2)$$

where $D_{2\%}$, $D_{50\%}$ and $D_{98\%}$ are defined as the dose values received by the 2%, 50% and 98 % of the PTV. For the OARs protection, it is of interest to compare $D_{25\%}$, as well as $D_{50\%}$, $D_{mean}$ and $D_{max}$.

## 3. Results

For each treatment plan, the dosimetric parameters of the PTV and OARs are presented in table 2. For P1 and P3 the HI were below 0.1 (HI = 0.07 and HI = 0.09, respectively), and presented an absolute difference of 0.02 between them. The obtained PTV coverage ($D_{95\%}$) was greater than 60 Gy and it was similar for both plans, while $D_{max}$ was 1.9 Gy higher for P3 than for P1.

**Table 2.** Dosimetric parameters of PTV, rectum and bladder for the P1, P2 and P3.

| Structure | Parameter | P1 | P2 | P3 |
|---|---|---|---|---|
| PTV | HI | 0.07 | 0.12 | 0.09 |
| | $D_{95\%}$ (Gy) | 60.1 | 58.8 | 60.1 |
| | $D_{mean}$ (Gy) | 62.0 | 61.7 | 62.3 |
| | $D_{max}$ (Gy) | 64.6 | 67.0 | 66.5 |
| Rectum | $D_{mean}$ (Gy) | 32.9 | 22.0 | 27.8 |
| | $D_{50\%}$ (Gy) | 34.6 | 13.7 | 22.7 |
| | $D_{25\%}$ (Gy) | 49.8 | 36.2 | 47.0 |
| | $D_{max}$ (Gy) | 62.2 | 65.0 | 65.3 |
| Bladder | $D_{mean}$ (Gy) | 16.9 | 9.1 | 11.8 |
| | $D_{50\%}$ (Gy) | 24.3 | 8.2 | 11.5 |
| | $D_{25\%}$ (Gy) | 25.5 | 9.4 | 14.7 |
| | $D_{max}$ (Gy) | 61.9 | 62.8 | 65.1 |

Figure 5 shows the DVHs obtained for each plan. It can be observed that the dose at the OARs decreases in P3 when compared to P1. In the rectum and bladder, $D_{mean}$, and $D_{25\%}$ were lower for P3, and $D_{50\%}$ decreases by around 34% of the value obtained by P1 for the rectum, and in the case of the bladder there is a reduction of more than 50% (see Table 2 and Figure 5a). In contrast, the maximum dose increased for P3 by 3.1 Gy for the rectum and 3.2 Gy for the bladder.

On the other hand, for P2, it is possible to observe in Figure 5a a greater reduction in the dose received by the OARs in comparison to P1 and P3. However, results presented in Figure 5b for the PTV show that the shoulder (cold spots), and the tail (hot spots) regions in the DVH are broader for P2. This implies a larger dose of inhomogeneity. In this way, the PTV

coverage decreases below the desirable value ($D_{95\%}$ < 60Gy), and its HI increases to 0.12 (see Table 2).

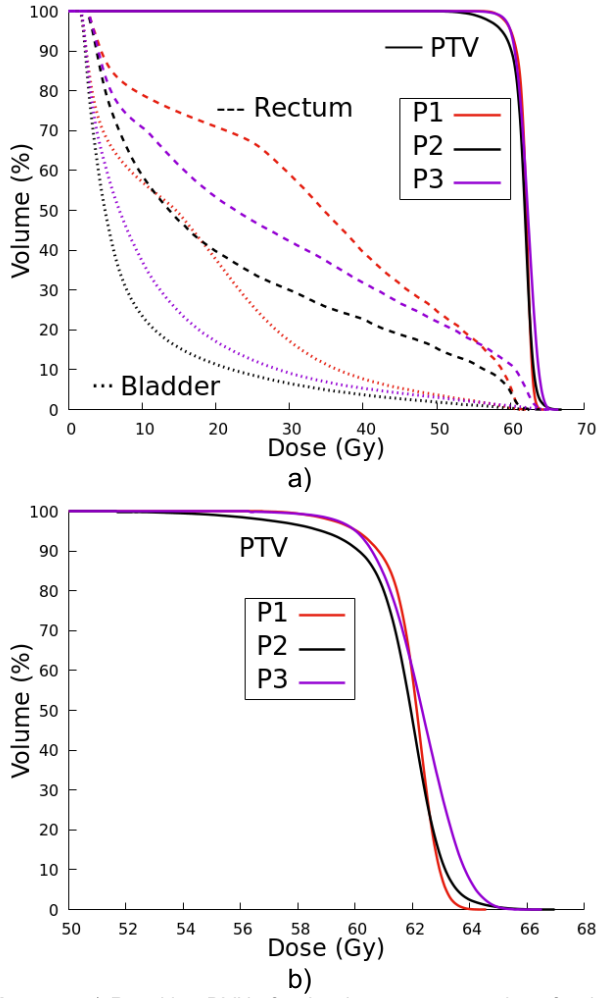


**Figure 5.** a) Resulting DVHs for the three treatment plans for the PTV (solid line), rectum (dashed line) and bladder (dotted line). b) DVHs for PTV showing the shoulder and tail regions.

## 4. Discussion

When comparing the three treatment plans, it was possible to observe that the least efficient route to reach the optimal level of protection for the OARs is by limiting the PTV coverage (as in P1). In contrast, by maximizing the OARs protection and by disregarding the PTV coverage (consequently compromising it, as in P2), has the advantage of reducing the dose levels. This results in lower dose values in normal tissues, but inadequate PTV coverage, which can diminish the efficiency of the radiotherapy treatment to achieve tumor control. This is far from the optimal scenario.

On the other hand, results obtained through P3 has shown an optimal balance between PTV coverage and homogeneity and sparing at the rectum and at the bladder. With the help of $R_1$, $R_2$, and $R_3$, $P_3$ allowed us to efficiently recover the coverage lost in P2, given the subsequent recovering from $R_1$ to $R_3$. In this regard, the coverage of the smallest sub volume, $R_1$, is straightforward to achieve in the optimization process than in the cases of the larger ones ($R_2$ and $R_3$). It is also true for $R_2$ with respect to $R_3$, leading to a continuous improvement of the whole PTV coverage. In addition, $R_4$ and $R_5$ provide the finest control over the hot spots at the DVH. According to this, P3 represents an optimal treatment plan, since it diminishes the dose at the OARs in comparison to P1, and substantially increases the PTV coverage with respect to P2.

It also must be observed that, when implementing P3, care should be taken with possible increments of the maximum dose at the OARs, especially for normal tissue overlapping with the PTV. To keep control of the maximum dose and avoid undesired increases, authors recommend including an upper objective with the same parameters than those for the PTV at the optimization process for the overlapping volume (denoted by Intra_OAR and defined through Figure 3b, see Table 1).

## 5. Conclusions

Creating auxiliary structures to recover the coverage constitutes a practical and effective method for radiotherapy treatments, allowing to considerably reduce dose levels at the OARs. It provides PTV coverage higher than 95% and homogeneity indices lower than 0.1. This represents a powerful resource for medical physicists and dosimetrists in treatment planning optimization processes.

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